

# PAPER FOR ICAME 2010 AT SVNIT, SURAT

## DIGITAL SIMULATION OF ENGINE OPERATING CHARACTERISTICS

Jigar Sura<sup>1</sup>, S. Ramamurthy<sup>2</sup>, Niyati Shah<sup>3</sup>

<sup>1</sup>Lecturer, Aeronautical Engineering Department, SVIT, Vasad, jigar\_sura@yahoo.com

<sup>2</sup>Scientist, Propulsion Division, NAL, Bangalore, ramamurthy\_srm@yahoo.com

<sup>3</sup>Lecturer, Aeronautical Engineering Department, SVIT, Vasad, niyati\_svit@yahoo.com

---

*Gas turbine has been making impact in variety of applications in recent time. With development of the gas turbine it has become critical to get accurate information of its behavior at the design stage. Customers demand guarantees of the response rate at the proposal stage. Transient performance deals with the operating regime where engine performance parameters are changing with time. The dynamic response of the gas turbine cannot be investigated experimentally until the program is well advanced. The simulation techniques, if used, using mathematical models permit the investigation of the dynamic behavior at early stage of design. This also helps in designing control systems for the gas turbines. The paper deals with the development of an aero-thermodynamic model for a single-spool turbojet engine. The mathematical model of the gas turbine has been developed and analysis has been carried out using software.*

### 1. Introduction

The gas turbine has made a great impact on the society as they are used in many areas from jet engines to simple mechanical drives. The response rate of the gas turbine is important in certain applications such as turbofan engines and lifting engines of VTOL aircraft. In earlier times, the response of the gas turbine engine was predicted experimentally. But today due to availability of advanced computing technology and detailed knowledge of the physical systems, simulation of the gas turbine engine can predict the behavior of the engine very accurately. Also, the flexibility of introducing different conditions such as icing, bleed helps predicting the transient behavior of gas turbine considered without damaging the actual engine.

Extensive research is going on in the field of digital simulation of aircraft gas turbine engines. Different methods to simulate the aircraft gas turbine engine by considering it as a linear system have already been developed. From 1950s, the gas turbine is treated as a nonlinear system. Investigated compressor and turbine operating trends and effect of division of over-all design overall pressure ratio on acceleration of the engine has been discussed here. Here the code is developed to simulate the gas turbine engine on computer. The code contained the steady state maps of the engine components.

The paper deals with the development of the aero-thermodynamic model of a single spool gas turbine engine and the simulation for the engine running line has been carried out. The effect of different fuel schedule, moment of inertia and combustion chamber volume has been investigated. The code has been written in Visual Basic 6. The interpolation routine has been developed.

### 2. Gas Turbine Simulation

For the simulation of the gas turbine engine, first the steady state data in terms of maps and characteristics of the components are obtained. From the ambient conditions and flight Mach number and the conditions at the engine intake are calculated. Using the efficiency of the intake and ram recovery factor, the conditions at the compressor inlet are calculated. Having known the engine rpm, this fixes the point on the compressor map. The pressure ratio across the compressor and isentropic efficiency are obtained from the compressor map. The fuel is added in the combustion chamber. Using the combustion efficiency (either constant or from the map if available) and calorific value of the fuel, the conditions at the turbine entry are obtained. From these conditions the turbine pressure ratio and efficiency are obtained from the turbine maps. This will give the conditions at the nozzle inlet. From the exit area and efficiency of the nozzle, the thrust is calculated.

In steady state condition there is no accumulation of mass or work imbalance at any point in the system. But during the acceleration or deceleration this is not the case. Fuel is added to accelerate the engine which increases the turbine inlet temperature which in turn increases the specific volume of the gas entering the turbine. As turbine is choked it cannot handle the increase mass flow. So the compressor mass flow rate has to decrease. So compressor moves towards the

surge line. The turbine now produces the more power than required to drive the compressor and other accessories. So the compressor accelerates. The deceleration can be explained in the same way.

There are two methods to calculate the engine running line during acceleration or deceleration.

#### 1. Iterative Method

#### 2. Intercomponent Volumes Method

**2.1 Iterative Method:** It assumes that the mass flow compatibility is maintained throughout the engine. It means that when the fuel flow is changed, the pressures at different points in the engine changes at the same instance in such a way that can give flow compatibility throughout the engine. But in real, the pressures cannot change instantaneously. The mass gets accumulated at some intercomponent volumes which are taken care of in the second method.

**2.2 Intercomponent Volume Method:** It gives more realistic insight into the transient behavior of the gas turbine engine than the iterative method because it considers both flow compatibility as well as work imbalance for the calculation of engine transients. Fig.1 shows the flow diagram used in the analysis.

The program has been written in Visual Basic to provide GUI. The required files are compressor and turbine characteristic maps in the following format.

- Compressor or Turbine Pressure Ratio map: Mass Flow Parameter, Pressure Ratio, RPM
- Compressor or Turbine Efficiency map: Efficiency, Mass Flow Parameter, RPM

Thus four data files are required. The path of each file should be given separately.

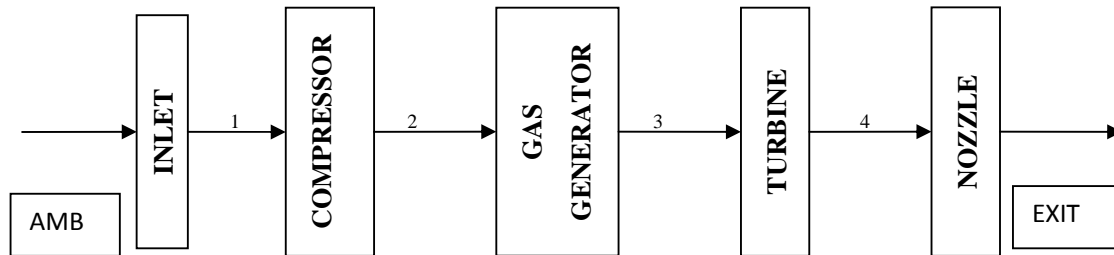


Figure 1 Flow Diagram For Turbojet Engine

### 3. GOVERNING EQUATIONS

#### 3.1 Ambient Conditions:

The aero-engine ambient conditions are not fixed but vary according to altitude. The ambient temperature ( $T_{amb}$ ) is a function of pressure altitude while ambient pressure ( $P_{amb}$ ) is a function of ambient temperature and pressure altitude.

Table 1 Ambient Conditions

| ALT (m)                       | Tamb (K)                             | Pamb (bar)                                               |
|-------------------------------|--------------------------------------|----------------------------------------------------------|
| <11000                        | $288.15 - 0.0065 * ALT$              | $1.01325 \left( \frac{288.15}{T_{amb}} \right)^{5.2561}$ |
| $\geq 11000$ and $\leq 24994$ | 216.65                               | $\frac{0.2268258}{0.000147766 * (ALT - 10996.4)}$        |
| $\geq 24994$ and $\leq 30000$ | $216.65 + 0.0029892 * (ALT - 24994)$ | $0.025287 \left( \frac{216.65}{T_{amb}} \right)^{11.8}$  |

#### 3.2 Ram inlet and exit conditions:

With the estimated ambient conditions and flight Mach number, the ram inlet pressure and temperature are calculated using the isentropic relations (1) & (2).

$$\frac{T_{01}}{T_{amb}} = 1 + \frac{\gamma_a - 1}{2} M_1^2 \quad \frac{P_{01}}{P_{amb}} = \eta_{inlet} \left[ \frac{T_{01}}{T_{amb}} \right]^{\frac{\gamma_a}{\gamma_a - 1}}$$

The ram inlet pressure is assumed to be a function of inlet isentropic efficiency and is expressed as  $\eta_{inlet} = 1$  if  $M_0 \leq 1$  and  $\eta_{inlet} = 1 - 0.0079(M_0 - 1)^{2.5}$ , if  $M_0 > 1$

In the real case, there are aerodynamic losses in the ram which are taken care of by considering the ram recovery factor, which is a function of flight Mach number. Thus the intake exit pressure is calculated as

$$P_{01} = RRF * P_{01}$$

### 3.3 Compressor:

Ambient air is sucked by the compressor through an inlet diffuser; the pressure of the air is raised by the compressor. From the characteristics map, for a known compressor pressure ratio and speed, the mass flow parameter and efficiency of the compressor are calculated by using interpolation technique. In real case, there will be some losses in the compressor which are incorporated by using isentropic efficiency. The stagnation temperature at the exit of the compressor is calculated by the equation given below.

$$T_{02} = T_{01} \left[ 1 + \frac{\gamma_a - 1}{\eta_c} M_1^2 \right]$$

The compressor power required can be calculated using the equation

$$P_c = \dot{m}_a (h_{02} - h_{01})$$

### 3.4 Combustor:

Heat input to the gas turbine engine is provided by a combustor. The combustor accepts air from the compressor and delivers it at an elevated temperature to the turbine. Combustor performance is measured by efficiency, the stagnation pressure decrease encountered in the combustor and the outlet temperature distribution. Here, the combustion efficiency has been considered as constant. The loss of stagnation pressure is assumed to be constant percentage of the compressor delivery pressure for the ease of calculation. The mass flow rate of fuel required for the given turbine inlet temperature is given by the equation given below.

$$\dot{m}_f = \frac{\dot{m}_a (c_{p_g} T_{03} - c_{p_a} T_{02})}{\eta_b Q_f - c_{p_g} T_{03}}$$

The stagnation pressure at the turbine inlet is

$$P_{03} = P_{02} \left( 1 - \frac{\Delta P}{P_{02}} \right)$$

### 3.5 Turbine:

The turbine extracts kinetic energy from the expanding gases that flow from the combustion chamber, converting this energy into shaft power. The pressure and temperature at the entry of the turbine has been assumed to be constant. From the characteristics map for the turbine, for a given speed and mass flow parameter the pressure ratio and the efficiency can be calculated.

### 3.6 Nozzle:

Hot gases leaving the engine exhaust to atmospheric pressure via a nozzle, the objective being to produce a high velocity jet. In this case, the nozzle is convergent and of fixed flow area. The nozzle may be choked or unchoked depending upon the pressure ratio across the nozzle and critical pressure ratio.

### 3.7 TRANSIENT ANALYSIS

A control volume approach is used to calculate the rate of change of pressure at the entry of combustion chamber.

$$\frac{dp_{01}}{dt} = \frac{d\dot{m} R T_{01}}{V_{01}}$$

The angular acceleration of the rotor is given by

$$\frac{dN}{dt} = \left( \frac{30}{\pi} \right)^2 \frac{W_t - W_c}{I * N}$$

The rate of change of temperature in the combustion chamber is given by

$$\frac{dT_{02}}{dt} = \frac{\dot{m}_c c_{p,c} T_{02} + \eta_b \dot{m}_f Q_f - (\dot{m}_c + \dot{m}_f) c_{p,g} T_{02} - (c_{p,g} - R) \dot{m} T_{02}}{\dot{m} (c_{p,g} - R)}$$

#### 4. RESULTS AND DISCUSSIONS

It should be noted that all the maps have been normalized with respect to the design condition value of the parameter.

The transient was run for different fuel schedules and the compressor characteristics were obtained as shown Fig. 2 and Fig.3. The fuel flow was increased from 20 % of design value to design condition in 10 seconds (Fig. 2). The results showed that while doing this kind of acceleration the compressor moves in the surge region. Same time was given for acceleration from 75% of fuel flow to design value (Fig. 3). It shows that compressor runs away from the surge line.

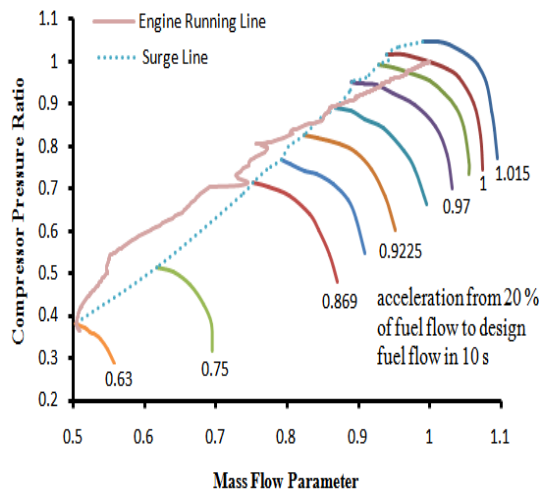


Fig. 2 Acceleration From 20% Fuel Flow To Design In 10 Sec

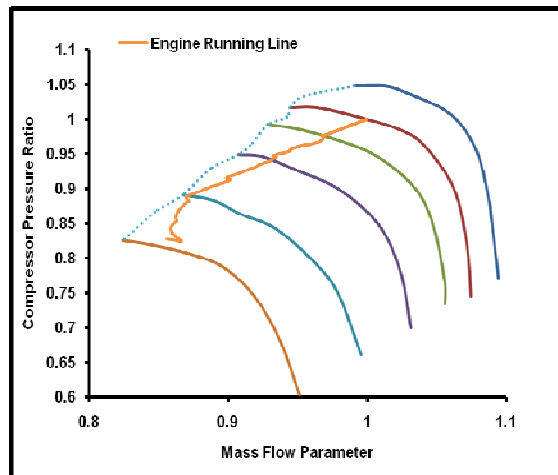


Fig. 3 Acceleration From 75% Fuel Flow To Design In 10 Sec

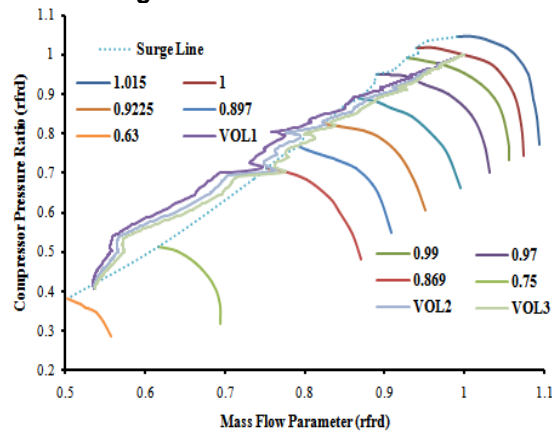


Fig. 4 Acceleration From 40% Fuel Flow To Design In 10 Sec

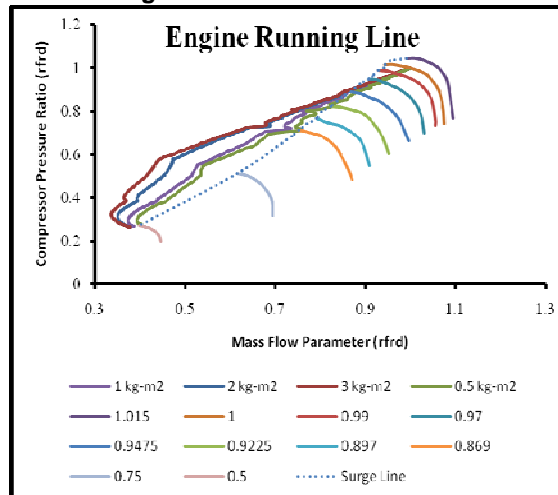


Fig. 5 Compressor Characteristics For Different Moment Of Inertia Of Engine

The transient had also been run for different Combustion chamber (Fig. 4) and different values of moment of inertia of the engine (Fig. 5). From Fig. 5 it is observed that for a given fuel schedule the higher value of inertia makes the engine running line to shift towards the surge line. Also time to reach the steady state condition increases with increase in moment of inertia. Also the size of intercomponent volume (combustion chamber volume in this case) was changed and the transient

was run. Fig. 4 shows that smaller size of combustion chamber makes the compressor to shift towards surge line.

## **5. CONCLUSION**

Some points can be concluded from the above results

- (1) The ramp change in the fuel should be made in such a way that the acceleration running line does not cross the surge line. This is not the case for the deceleration.
- (2) It can be concluded from this analysis that the combustion chamber volume does not play major role in transients of the engine.
- (3) The inertia of the engine plays the major role for turbojet engine.
- (4) With proper modification of the program it can be used for simulation of different conditions such as icing or breakage of shaft. Also, the simulation can help in designing the control system and also for the fuel scheduling of the aircraft engine.

## **6. ACKNOWLEDGEMENT**

This work has been carried as a part of dissertation for post graduation. The first author is thankful to Director, NAL and Head, Propulsion Division, NAL for providing the opportunity to carry out this work.

## **7. REFERENCES**

1. Otto, E. W. and Taylor, B. L., III, 'Dynamics of A Turbojet Engine Considered As A Quasi-Static System', *NACA*, TN 2091, 1950.
2. Ketchum, J. R. and Craig, R. T., 'Simulation of Linearized Dynamics of Gas-Turbine Engines', *NACA*, TN 2826, 1952.
3. Pack, G. J. and Phillips, W. E., Jr., 'Analog Study Of Interacting And Non-Interacting Multiple-Loop Control Systems For Turbojet Engines' *NACA*, TR 1212, 1955.
4. Gold, H. and Rosensweig, S., 'A method for estimating speed response of gas-turbine engines', *NACA*, RM E51K21, 1952.
5. Crooks, P. V., and Willshire, D. W., 'the theoretical estimation of engine speed response data for a turbojet engine', *NGTE*, M268, 1956.